

MICRO-OPTICS IS...

Phabulous

Pilot Line Technology Handbook

Providing highly advanced & robust manufacturing technologies for optical free-form micro-structures

www.phabulous.eu



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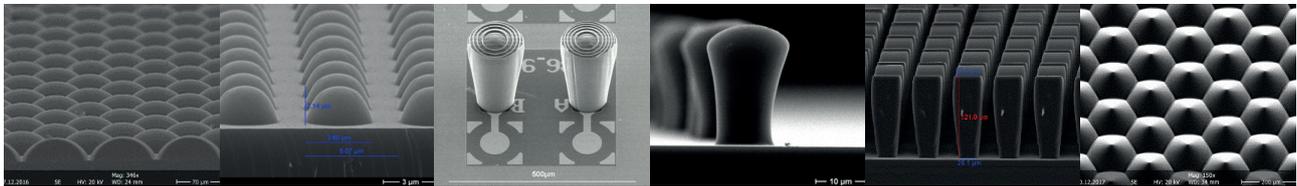
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Introducing PHABULOuS

A new era for free-form micro-optics

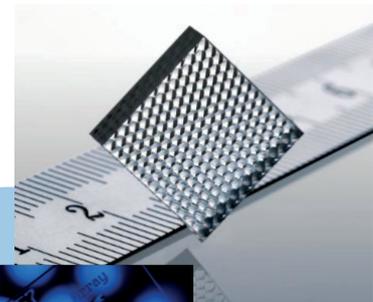
Free-form Micro-optics are micro-optical components:

- Designed with no symmetry constraints
- Enabled by innovative modelling
- Requiring ultra-precision machining



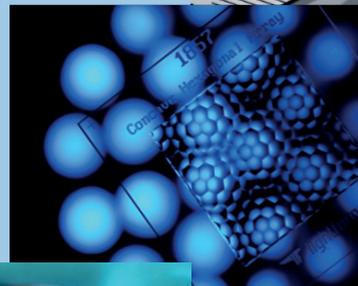
Innovative technology with various advantages

- New functionalities with aberration reduction
- Miniaturization & integration
- Low-weight & Large-area
- Flexibility & Conformability
- Low-cost mass manufacturing
- System simplification



Advanced technology

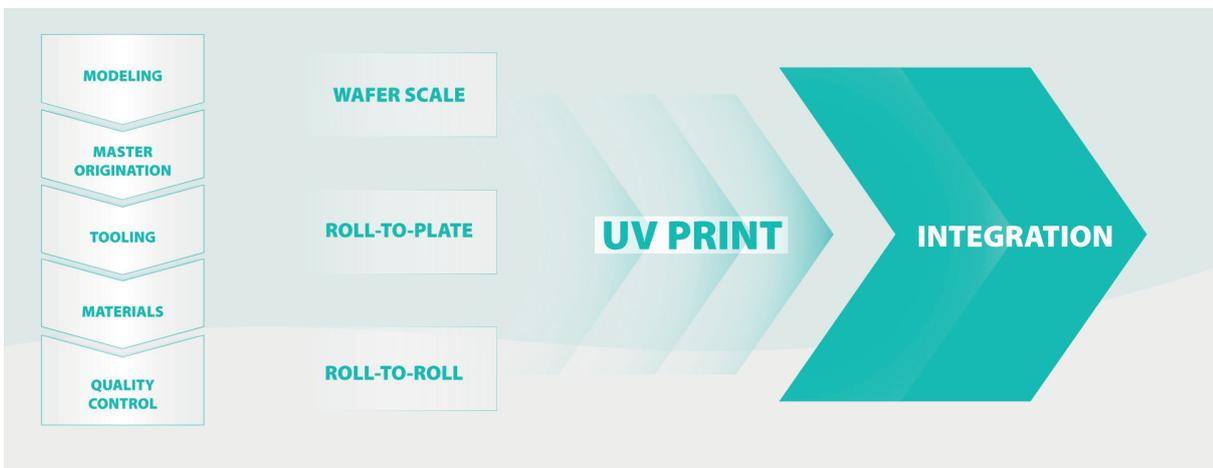
- Design
- Fabrication
 - Mastering
 - Up-scaling
 - Tooling
 - Replication
- Material
- Characterization
- Mass production
- Integration



Introducing PHABULOuS

Unique selling proposition

PHABULOuS offers a unique **one-stop shop** for all requests for prototyping and manufacturing of free-form micro-optics services: from pilot to full-scale production.



PHABULOuS's goal is the industrial manufacturing of innovative and highly demanded micro-optical components for **various photonics applications**, with a clear roadmap for high volume production in Europe at a competitive cost.



Introducing PHABULOUS

Pilot-Line Association

The Association is established within the framework of the H2020 European research project entitled “Pilot-Line Providing Highly Advanced & Robust Manufacturing Technology for Optical Free-Form Micro-Structures” funded by the European Commission (“PHABULOUS Project”).

The main objectives of the PHABULOUS Pilot-Line association are:

- Implement the PHABULOUS Project in accordance with the Grant Agreement n°871710
- Unify European research and technology organisations and industrial partners into a Pilot Line for the design and manufacturing of free-form Micro-optics solutions.
- Test the efficiency of the Pilot-Line concept through the validation of requests for piloting services within the implementation of the PHABULOUS Project.
- Promote advanced photonics technologies and solutions and offer a single-entry point (one-stop shop) in order to facilitate access to comprehensive problem-solving competency for the complete production chain, which is intended to continue after the PHABULOUS Project.
- Represent the interests of the PHABULOUS Pilot-Line community on a national and international basis.

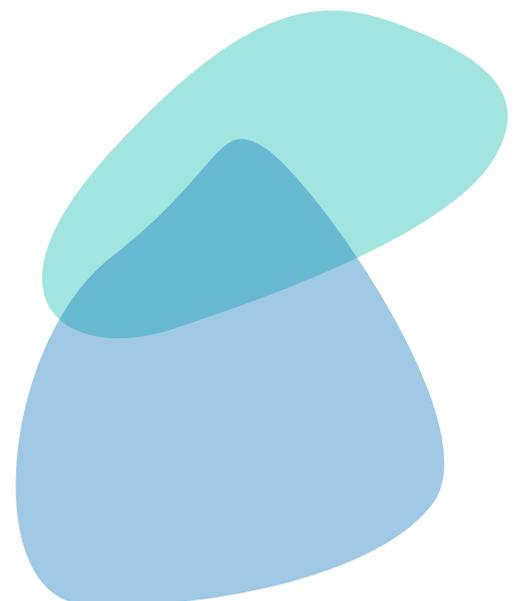
The Pilot-Line Front Office (PLFO) of PHABULOUS – An independent legal entity that will provide customers with a single-entry point to the Pilot-Line and its services in Europe, for SMEs and LMEs aiming to pilot and produce devices integrating free-form micro-structures. Contact our front office at info@phabulous.eu.

The PLFO will be responsible for dissemination, advertising, and outreach of the offered manufacturing services. It will create advertising material and will build up the PHABULOUS Pilot-Line corporate identity and design.

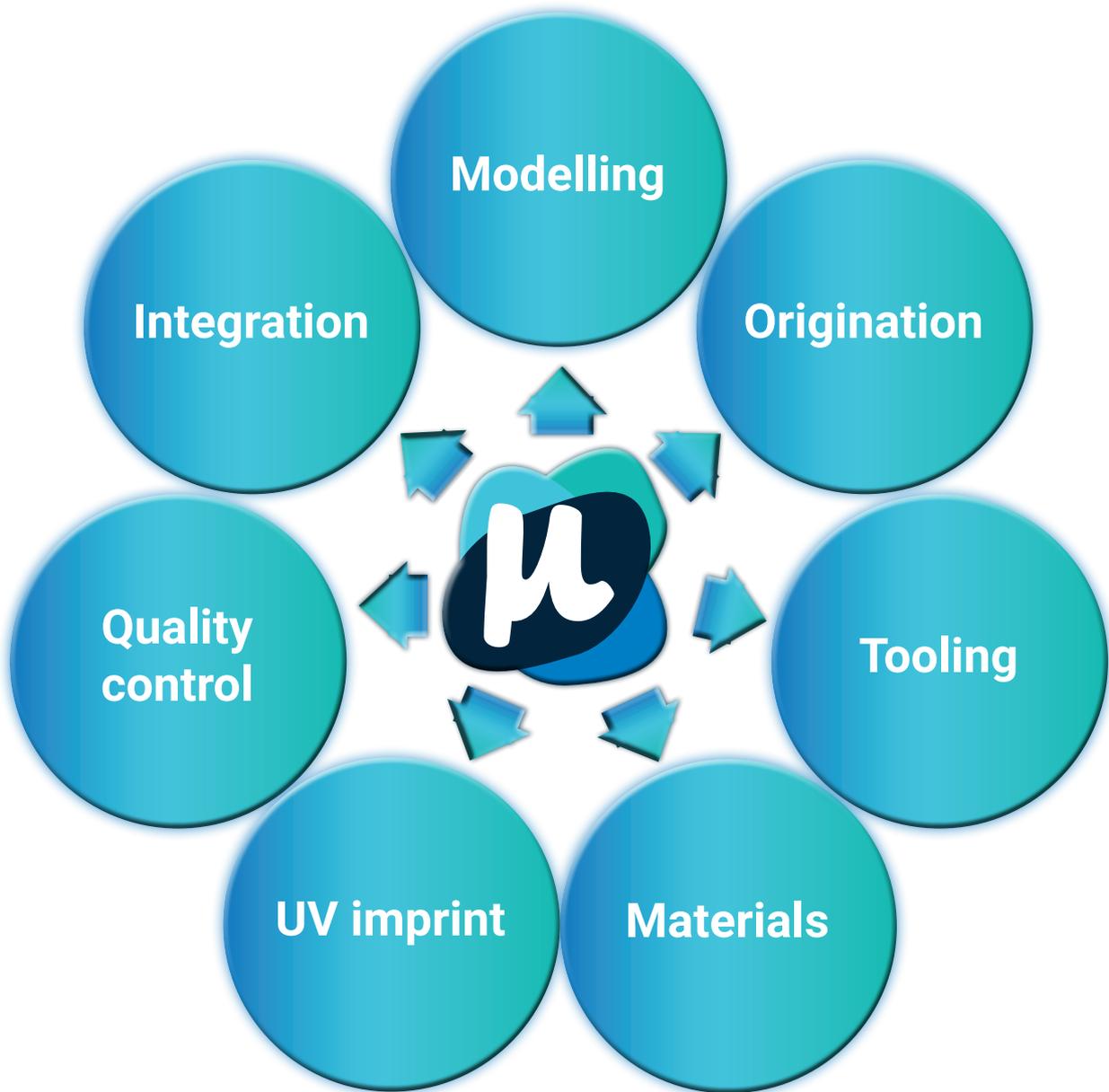
Free-form micro-optics industry

Prototyping Piloting Large volume production

- Accelerated innovation & production cycles: From modelling to manufacturing and quality control of free-form micro-optics
- Manufacturing services: Various replication and coating technologies
- Clear roadmap for high volume production at competitive cost



Introducing PHABULOuS



State-of-the-art Technologies

1 - Open design platform

The PHABULOU S Pilot Line aims to support customers from an early stage. With this objective, PHABULOU S will open a design platform where customers will benefit from our proprietary design toolbox.

The PHABULOU S Pilot Line design platform includes proprietary solutions for the design of free-form micro-lens arrays (FMLAs) based on customer specifications. Specifically, PHABULOU S will offer two complementary design approaches.

Indirect design – Using complex arrangements of well-known, manufacturable micro-structures, prescribed illuminance distributions (e.g. non-uniform) can be achieved. Developed for lighting applications, this approach ensures a rapid transition to a successful manufacturing and large integration tolerances.

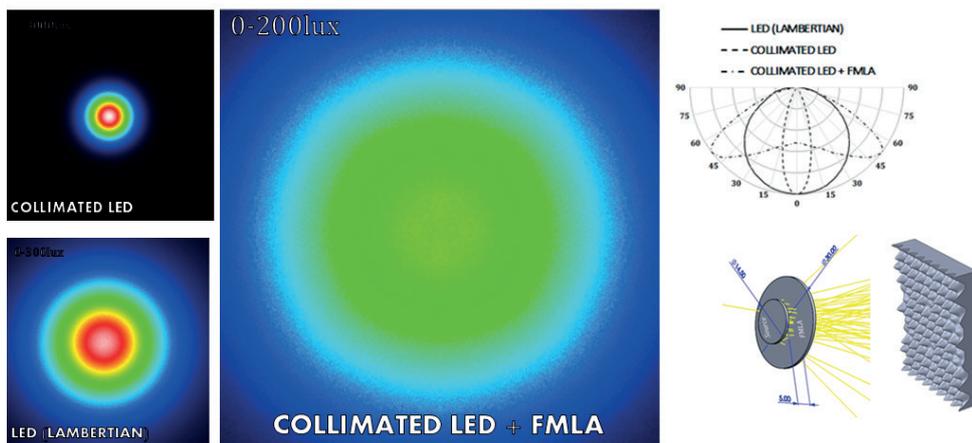


Figure 1: A narrow-beam LED is beam-shaped to a batwing LID (luminous intensity distribution) by a FMLA designed using the indirect design approach. Left) Far-field Illuminance distributions. Right-top) normalized candle-power plots. Right- bottom) ray-traced CAD models of the light source and FMLA.

Direct design (Ray-mapping) – Based on ray-mapping algorithms customized for micro-optical components, this approach is ideal for highly demanding illuminance distributions (e.g. asymmetric) where initial guesses on the micro-lens shape are not available.

State-of-the-art Technologies

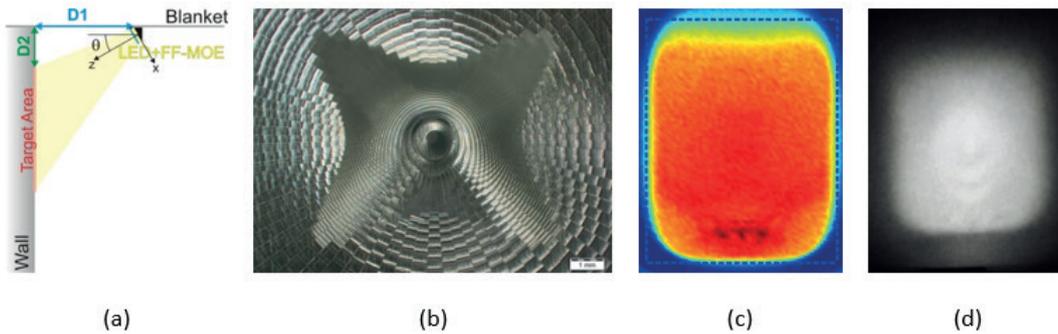
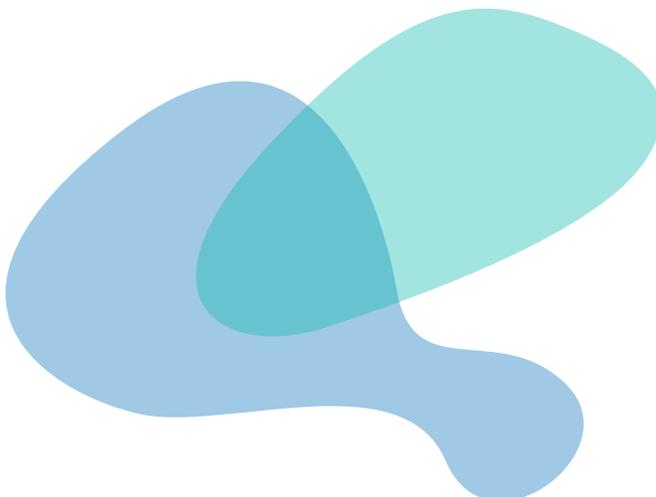


Figure 2: Asymmetric wall-wash lighting solution designed using the direct design approach. a) Schematic illustration of the optical system. An LED light source on the ceiling should homogeneously illuminate an oval target area on the wall. b) Designed the FMLA. c) and d) Predicted and measured illuminance distribution on the target area.

Design for manufacturing – The PHABULOU^S design toolbox comprises commercial design and simulation software tool such as ZEMAX, LightTools, LucidShape, Light Trans, FRED etc. coupled to enabling CAD modelling solutions (SolidWorks, CATIA, AutoCAD, Rhinoceros & Grasshopper, Resurf, etc.) and custom-made scripts (Python, MATLAB, etc.). With this toolbox, the PHABULOU^S design offer will be completed with design-for-manufacturing kits that will enable customers to:

- Provide their optical designs in the most common representation formats including point clouds, STL, IGES, STEP, and Polynomials.
- Validate their optical designs for manufacturability and select the most appropriate manufacturing technology.
- Quantify expected manufacturing deviations and predict performance degradation hence avoiding costly trial-error cycles.
- Provide design rules to fine tune the initial optical designs towards a successful production and a satisfactory optical performance.



State-of-the-art Technologies

2 - Origination: form accuracy & surface quality

PHABULOuS innovative technological offer – The large scope of applications targeted by PHABULOuS translates into a wide range of FMLA geometries and dimensions, tolerance levels and form accuracy and surface quality specifications. In order to broaden its technological offer, the PHABULOuS Pilot Line offers an extensive selection of origination technologies including additive and subtractive, mechanical and laser-assisted, mask-based and maskless. Specifically, the PHABULOuS Pilot Line currently offers diamond and laser micro-machining, two-photon absorption, maskless grey-scale lithography, fs-laser ablation, and photo-lithography/Si-etching.



Figure 3: MLA, FMLAs, and 3D nano-structures fabricated using a) DMM, b) LMM, c) FSLA, d) GSSL and e) LMP-TPA.

Diamond Micro-Machining (DMM) with demonstrated sub-micron form accuracy and nanometre surface quality is ideal for optical applications. (On-axis) diamond turning is especially well-suited for the manufacturing of micro-lens arrays but relies on the manual shifting of the workpiece. This is impractical for large micro-structure arrays due to the poor position accuracy, large balancing errors and long processing times.

Dynamic Part Indexing (DPI™), a patented technology available in PHABULOuS is an add-on to an ultra-precision diamond turning lathe that alleviates the mentioned limitations. DPI enables the automatic shift of the substrate for an efficient on-axis diamond turning of large lens arrays comprised of aspheres, freeforms or even diffractive optical elements. The table on the right compares DPI™ to three well-known free-form machining technologies namely Slow Slide Servo (SSS), Fast Tool Servo (FTS) and Diamond Micro-Milling (DMM). Further improvements of DPI™ will allow to achieve submicron positioning accuracy over large lens arrays or masters up to 8 inches.

	SSS	FTS	DMM	DPI™
Maximum slopes (α)	20	20	45	80
Process speed	-	+	--	+
Form accuracy (pv; in nm)	300	600	300	100
Roughness (Ra; in nm)	10	10	10	2
Ultrasonic turning	N	N	N	Y
Grinding	N	N	N	Y

State-of-the-art Technologies

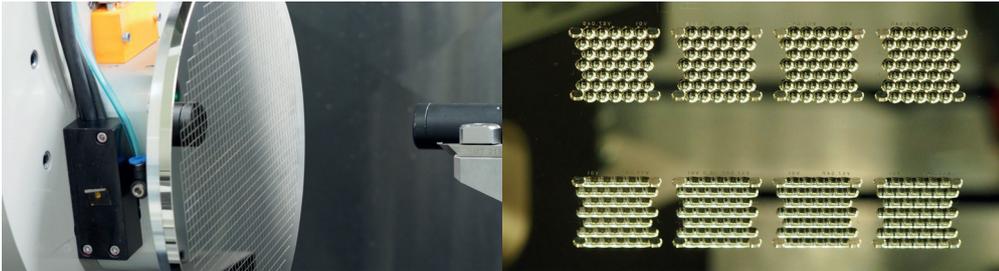


Figure 4: Diamond micro-turning: Dynamic Part Indexing (DPI™) for Micro lens arrays (MLAs). Left) 8" prototype MLA wafer. Right) Close-up view of machined FMLAs on a 8" wafer.

Laser Micro-Machining (LMM) is a direct-write micro-machining technology compatible with the manufacturing of fully free-form micro-optical components in fused silica in short time scales.

Laser Micro-Machining does not require product-specific hard tooling (such as moulds or photo-masks) and it hence ideal for rapid prototyping with low-cost design iteration. The sub-micron form accuracy and excellent surface quality (nanometre surface roughness) demonstrated by PHABULOuS. LMM makes it very attractive as an origination process for large-volume UV-imprinting replication.

The Laser Micro-Machining equipment available in PHABULOuS is highly automated on (4" maximum) wafer-scale with a throughput of ~ 1 cm²/h (for 100 µm height) and can currently produce free-form micro-structures with in-plane sizes of up to 100 µm, structure heights in the (5-250) µm range and up to 30° slope angles.

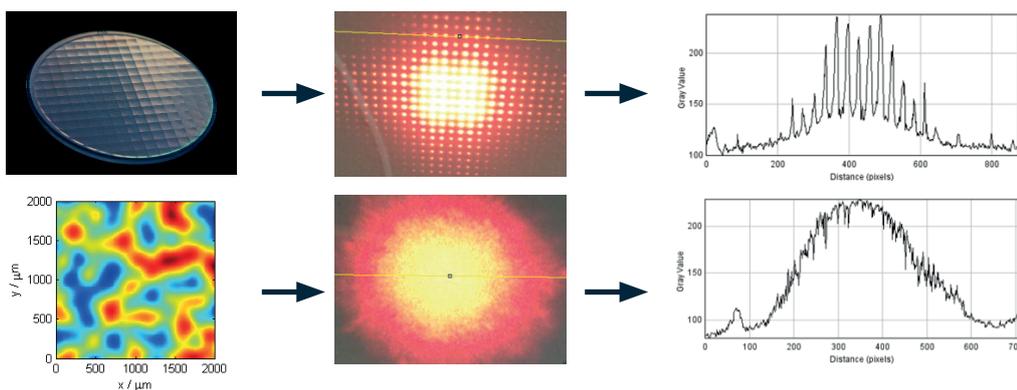


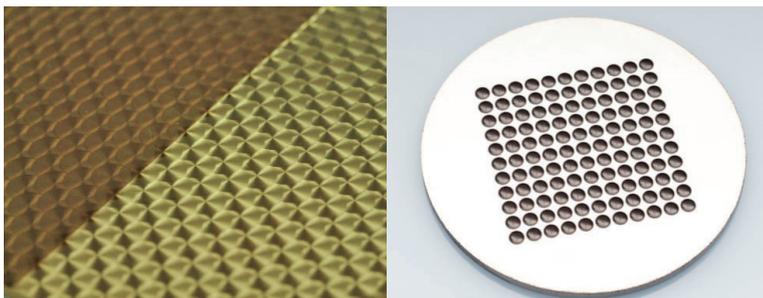
Figure 5: Laser micro-machined FMLAs (PRIME Beam-shapers). Top) Lens Array with Low M2 Beam. Bottom) PRIME with Low M2 Beam).

State-of-the-art Technologies

Two-Photon Absorption (TPA) enables full three-dimensional structuring of arbitrarily complex models with a resolution in the submicron range. Although well-established on a laboratory scale, industrial level throughput has not been demonstrated yet.

Greyscale laser lithography (GSL) is compatible with the origination of FMLAs with optical quality surfaces. The key features have a minimum lateral feature size of 200 nm, a maximum structure height of around 50 µm (aspect ratio of 1:4) with an accuracy of 80-85%.

Femtosecond laser ablation (FSLA) enables fast and contactless machining of embossed designs with perfectly monitored dimensions. This technique demonstrated highly asymmetrical shapes on many different substrate materials.



Polished « Perlage » (Gold)

Micro cavities (Stainless steel)

Figure 6: Example of micro-structures originated with FSLA technology on 1 cm diameter stainless steel substrate (LASEA).

Photo-lithography and Si-etch (Si-E) – PHABULOU S offers a unique photo-lithography portfolio in combination with appropriate dry or wet etching capabilities to support the origination needs: depending on the requirements, very specific and designed Free-form structure will be originated from either a standard 193 nm optical lithography, and/or using Maskless lithography (ML2) and/or Direct Self Assembly (DSA) and/or (nano) imprint and/or combination of these options. For that purpose, a standard 2D shape is first achieved by photo-lithography and subsequently transferred to the final substrate via etching to obtain the desired 3D FMLA structure.

State-of-the-art Technologies

PHABULOUS ambition – The PHABULOUS Pilot Line is currently (and will continue to) committing considerable efforts to accelerate all the origination technologies Beyond the State of the Art. Our ambition is summarized in the table below.

Technology	PHABULOUS ambition (Beyond state-of-the-art)
Diamond micro-machining	Increased throughput by a factor of 3 (indexing time reduction from 15 to 5 seconds) Increase maximum slope angles from 45 up to 60° (with metrology) Improve lens positioning accuracy over large lens arrays or masters down to 1 µm
Laser micro-machining	Increase throughput by a factor of 2 Increase clear aperture from 2 to 4 inch Increase maximum angles from 30° to 60° (with metrology) Increase maximum lateral dimensions from 100 to 250 µm
Femto-second laser ablation	Increase writing resolution from 2 µm to 1 µm Reduce surface roughness, from several 100's nm down to 10 nm (RMS)
Greyscale laser lithography	Maximum height increased from 50 µm up to 150 µm Lateral dimensions between 0.4 - 500 µm Form accuracy increased from 80% to 95% Single optical element size (lateral) between 5-500 mm
Two-photon absorption	Increase manufacturing throughput by a factor of 5 Increase scanning speed by a factor of 10 Reduce surface roughness, from 10's nm down to 10 nm (RMS) Lateral vertical dimensions between 0.1 - 500 µm (5-100 µm)

Optical components require high accuracy (sub-micron) manufacturing to ensure compliance with customer specifications. FMLAs optical designs often comprise angular and linear dimensions largely dissimilar making accurate manufacturing extremely challenging, time consuming and expensive. Moreover, the origination time and cost increases (nearly) quadratically with increasing area, a limitation for large-area applications. The PHABULOUS Pilot Line addresses this limitation by complementing the previously described origination technologies with upscaling, tooling, and large-area UV imprint replication technologies described in the following sections.

State-of-the-art Technologies

3 - Upscaling and Tooling

Upscaling for UV imprint replication – In analogy with optical lithography steppers, the so-called UV imprint step-and-repeat (S&R) technology enables the up-scaling of small masters to large-area tools for subsequent large-area replication thus keeping the origination effort limited to small areas and affordable cost.

Large-area applications often **demand for seamless working masters/ tools** where the adjacent FMLAs are precisely positioned in contact to one another, i.e. with negligible gaps or alternatively with well-controlled slight overlapping.

PHABULO μ S S&R technology has demonstrated 20-50 μ m stitching accuracy (gap or overlapping). The ambition is to reduce this figure down to 1-5 μ m, which corresponds to 1-10% of the typical lateral dimensions of the FMLA features.

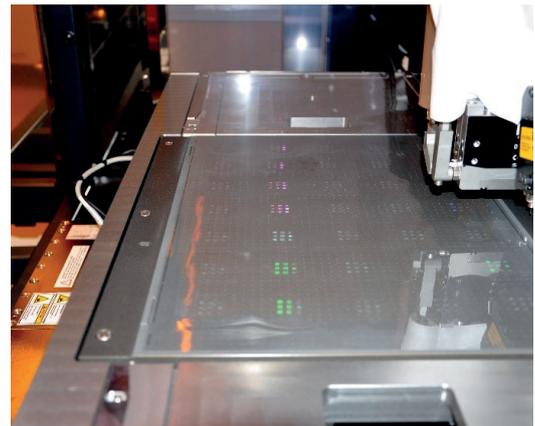
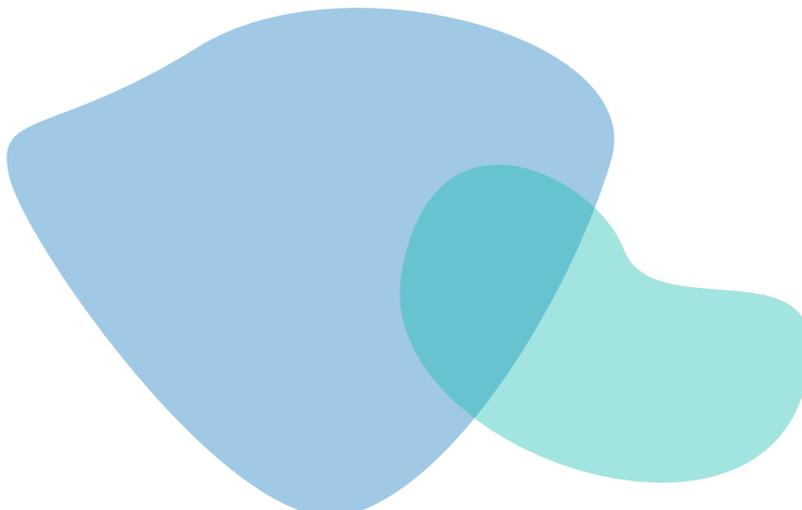


Figure 7: Production of flexible embossing tools for roll-based UV imprint replication.

For roll-based replication specific tools need to be manufactured. Depending on the replication technology, we offer:

Tool production for R2P UV imprint replication (Large-area soft stamps) – Tool up-scaling is also achievable by tiling multiple small-area masters on a large-area flexible stamp.

Tool production for R2R UV imprint replication (Electro-formed Nickel shims) – A galvanic electroplating process is used to transfer micro-structured surface of the up-scaled master onto a robust (but flexible) replication tool (Nickel shim) for subsequent high-throughput and cost-effective wafer-scale or roll-to-roll (R2R) UV imprint replication.



State-of-the-art Technologies

Main advantages of PHABULOUS up-scaling and tooling technologies		
Step-and-repeat (S&R)	Large-area soft stamps	Electro-formed Nickel shims
Cost-effective	The large-area flex stamp can be re-used over 500 to 1000 times, and is thereby highly cost-effective.	Cost-effective and reproducible replication of master with minimal quality variation. A high number of nickel tools can be manufactured from a single master.
Industry-compatible	The possibility to tile multiple products on the large-area soft stamp enables high-volume production volumes.	High resolution and good replication fidelity.
Step & Repeat imprint method has accurate positioning within 5 µm	Roll-to-Plate imprint alignment accuracy from large-area soft stamp to substrate is well below 100 µm. Developments ongoing for industry-compatible soft-stamp to substrate alignment accuracies of below 10 µm.	Good mechanical durability and chemical resistance of the tool.
Flexible	The Roll-to-Plate imprint technology is flexible; the large-area soft stamp can be changed easily in few minutes, imprinting same or a different nano or micron-structure.	Chemical modifications of the nickel replication reel for extension of the reel lifetime. Cleaning of the nickel tool can further extend the tool lifetime.

The ambition of PHABULOUS is to produce replication tools with areas up to 200 mm round for wafer-scale, 600x1000 mm² and up to 1100x1300 mm² for Roll- to-Plate (R2P), and 450x450 mm² for Roll-to-Roll (R2R) with a stitch width and height below 5 and 10 µm, respectively, using a S&R approach and to increase tool lifetime by at least 80% through the development of new handling/cleaning and packaging/transport procedures.

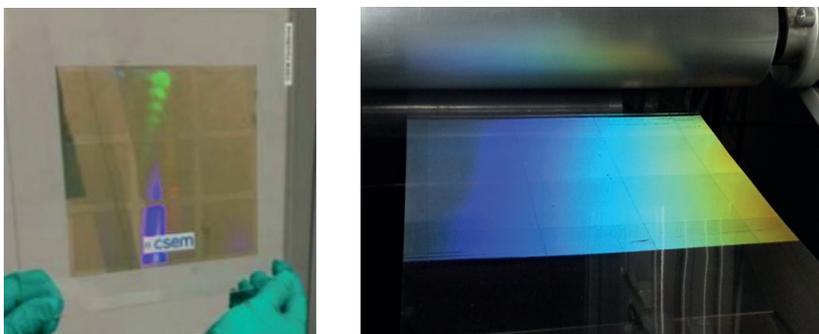
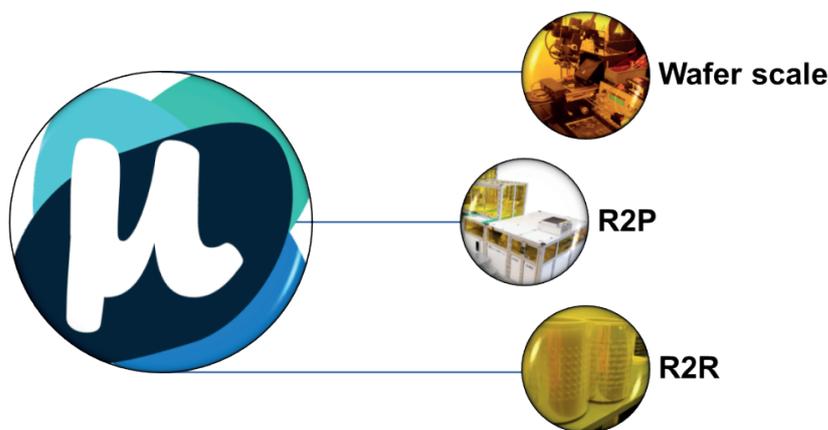


Figure 8: Left) Plasmonic gold nano-structures fabricated with a step-and-repeat UV casting process, resulting in a 15x15 cm² sample. Right) Sheet with a 2D diffractive nano structure for enhanced in coupling for thin film photovoltaics.

State-of-the-art Technologies

4 - Large-area UV imprint replication

PHABULOuS provides three different technologies for the cost-effective, high-throughput large-area UV imprint replication technologies. The table below summarizes the ambitious maximum area and capacity.



Replication pillar / Property	Wafer scale	Roll-to-Plate (R2P)	Roll-to-Roll (R2R)
Maximum surface area (others)	200 mm diameter	1100x1300 mm ² plates	500mm web width* (production line) 240 mm (R&D line)
Maximum surface area in PHABULOuS	300 mm diameter**	550x650 mm ² and up to 1100x1600 mm ² plates	500 mm web width* (production line) 240 mm (R&D line)
Yearly capacity (others)	10000 wafers	4000 plates***	1500 km/line (production line) 200 km/line (R&D line)
Yearly capacity in PHABULOuS	30000 wafers**	2000 plates	200 km/line (production line) 25 km/line (R&D line)

*480mm micro-structured width; ** With the production ramp-up planned by PHABULOμS partner SUSS Micro-optics (Excellence Center);

***Up to 250000 plates possible depending on equipment used

State-of-the-art Technologies

UV imprint replication of FMLAs with sub-micron form accuracy – UV imprint replication is an extremely promising technology for the low-cost and high throughput replication of complex 3D micro and nano-structures with ultra-high precision. The recent development of large-area UV imprint processes has enabled the mass manufacturing of large-area micro/nano-structures thereby enabling new commercial applications.

Wafer-scale UV imprint replication comes with key features such as layer-to-layer alignment and front-to-back alignment and multi-stacking capabilities. On the other hand, it enables complex processes such as wafer-level packaging and direct connection to optoelectronic components.

Combining this technology with free-form optics addresses new markets (such as AR/VR, automotive lighting, CMOS imager and displays) which demand for high performance, low cost, and compactness. The technology is already available and running in high volume for the automotive market, but is not yet applied to FMLAs.

Main advantages of PHABULOuS Wafer-scale UV imprint replication technology	
Maximum structures height	500 μm
Minimum residual layer thickness	$\approx 20 \mu\text{m}$
High alignment accuracy of components	3 μm in wafer plane and 10 μm normal to waver plane
Various lens materials	Hybrid sol-gels (solvent free) and Epoxies
Process on	Wafer up to 200 mm diameter (upgrading to 300 mm diameter)
Form accuracy of structures / optical quality of surfaces	< 20 nm rms

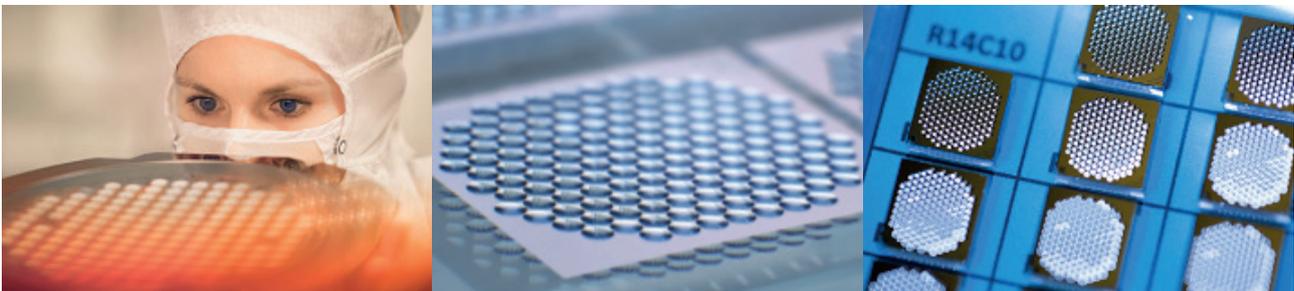


Figure 9: Micro-imprint fabrication of micro-optical elements. Micro-optics is fabricated on wafers of 200 mm diameter and separated by dicing. Each micro-optical element has more than 100 channels to realize its functionality. The multichannel concept together with free-form optical design allows to realize illumination and imaging of objects with extraordinary homogeneity and no deformation.

State-of-the-art Technologies

Roll-to-Plate (R2P) UV imprint replication technology focuses on three fundamental aspects namely the technology scalability, cost effectiveness (large area & high volume) and compatibility with available production lines. Currently there are many proven processes for textures well below 100 μm height, shrinkage around 5% and industry-compatible manufacturing yields that are highly design dependent.

Main advantages of PHABULOUS R2P UV imprint replication technology:

- Provide their optical designs in the most common representation formats including point clouds, STL, IGES, STEP, and Polynomials.
- Validate their optical designs for manufacturability and select the most appropriate manufacturing technology.
- Quantify expected manufacturing deviations and predict performance degradation hence avoiding costly trial-error cycles.
- Provide design rules to fine tune the initial optical designs towards a successful production and a satisfactory optical performance.

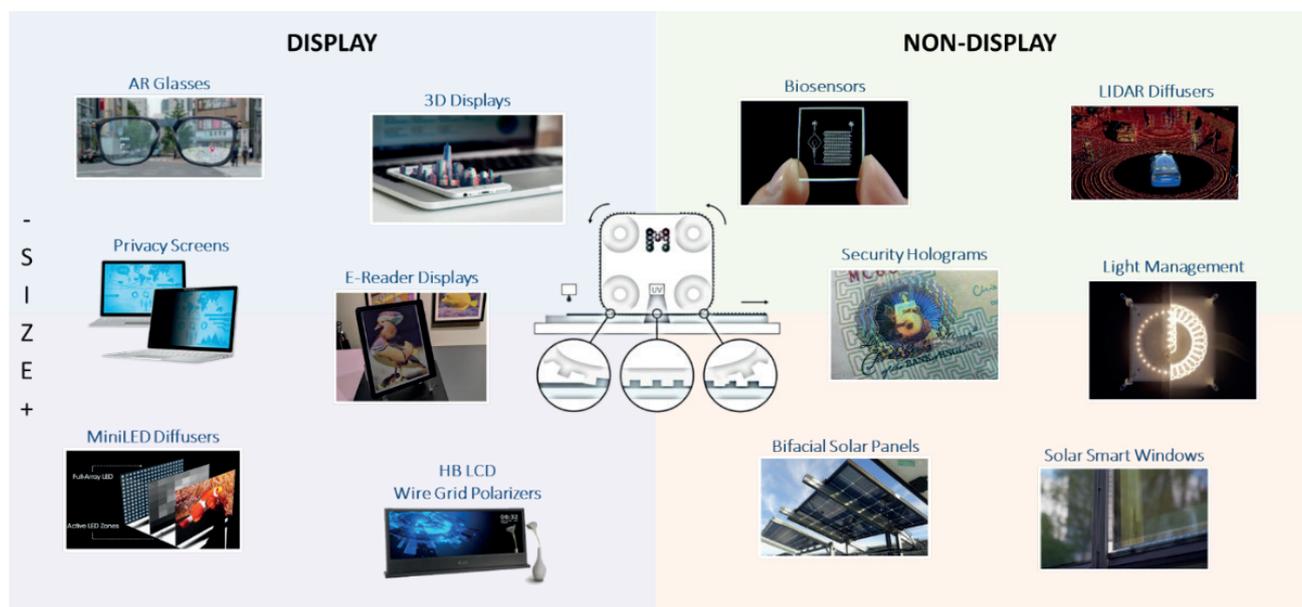


Figure 10: The R2P technology can be used for different applications where precise micron or nano-scale structures are needed at high volume and commercially viable costs.

State-of-the-art Technologies

Roll-to-Roll (R2R) UV imprint replication is a high-resolution fabrication method, which is characterized by a high throughput and cost-effectiveness. In the continuous R2R replication process, an UV curable resin is used to replicate the desired structures from a cylindrical tool to a flexible substrate. It has been utilized in the mass-production of optical components, including light guides, diffractive optical elements and microlens arrays. R2R UV imprint replication has demonstrated the replication of high-resolution micro and nano-structures with length scales far below those associated with the traditional manufacturing technologies of plastics (e.g. injection moulding). A detailed comparison between R2R UV imprint and two common competing replication technologies is presented in the table on the next page.

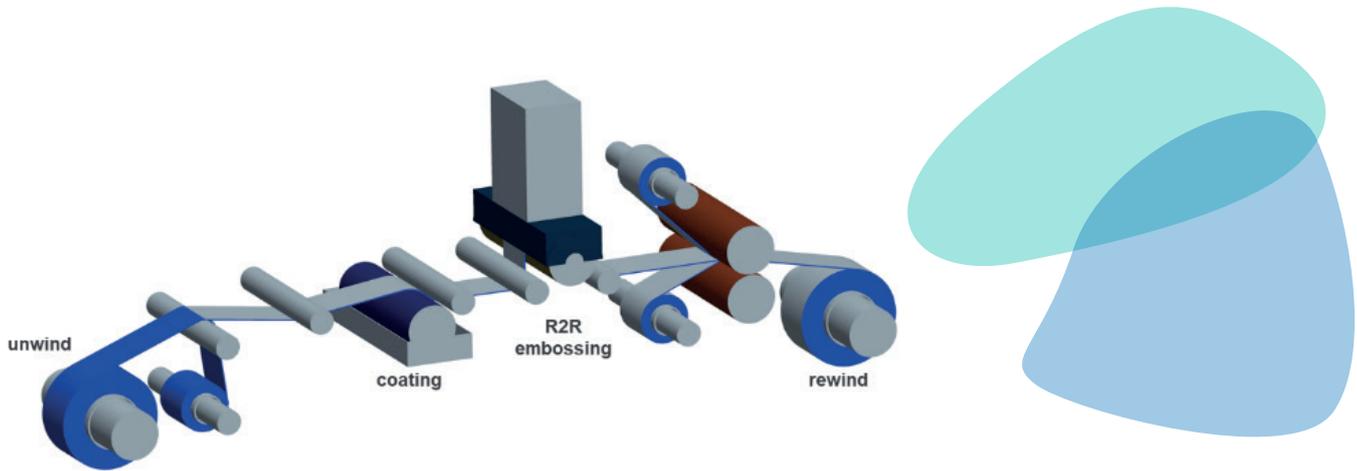


Figure 11: A schematic presentation of the R2R UV imprint process (Nanocomp).

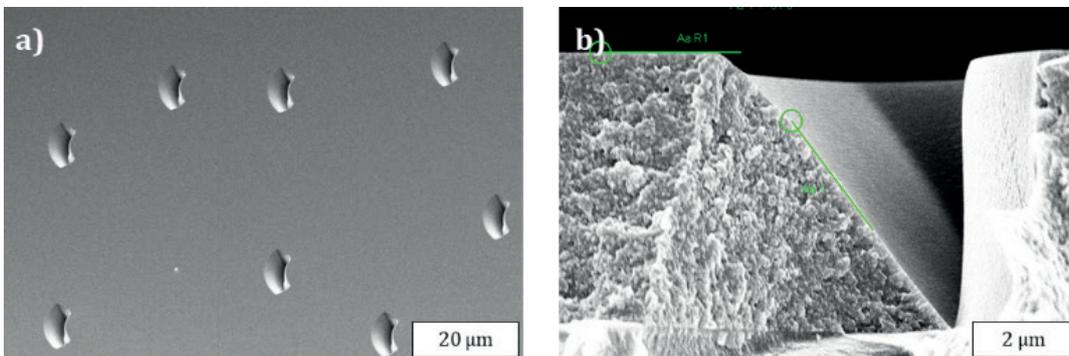


Figure 12: Top view (a) and X-section (b) SEM images of prismatic micro-structures replicated using PHABULOUS R2R UV imprint (Nanocomp)

State-of-the-art Technologies

Technology	Advantages	Disadvantages
Injection moulding	<ul style="list-style-type: none"> High speed, automated production Standardized materials Solvent-free process No post-processing needed 	<ul style="list-style-type: none"> High tooling cost No thin-film compatible Limited aspect ratio Low resolution (incomplete mould filling)
R2R Hot embossing	<ul style="list-style-type: none"> High speed and low cost Standardized materials Thin-film compatible Solvent-free process 	<ul style="list-style-type: none"> Limited optical properties (raw materials) High temperature and pressure process Requires post-processing (cutting)
R2R UV imprint	<ul style="list-style-type: none"> High resolution and aspect ratio High replication fidelity at high/moderate speeds Tailor-able mechanical, chemical and optical properties of the UV resins Thin-film compatible Room temperature and low-pressure process Solvent-free/solvent-based process Single-step lamination and coating of samples possible 	<ul style="list-style-type: none"> Requires post-processing (cutting) Challenging de-moulding for high aspect ratio micro/nano-structures

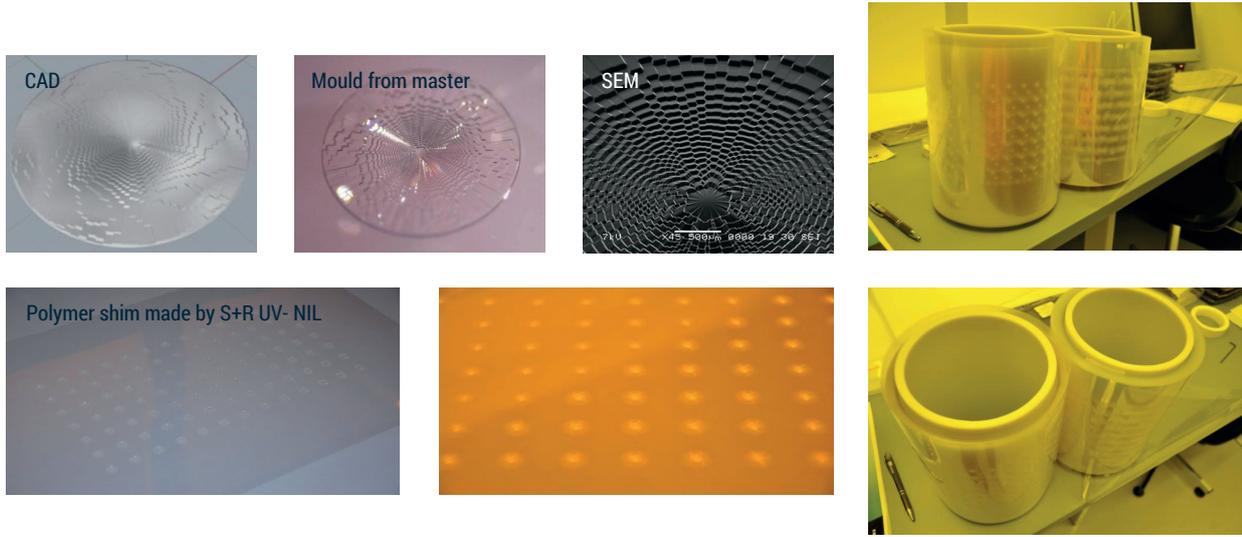


Figure 13: Mastering and replication of FMLAs by JOANNEUM Research Institute

State-of-the-art Technologies

Replication Technology

PHABULOU S ambition (Beyond state-of-the-art)

Wafer scale

Wafer-scale UV imprinting of free-form micro-optics featuring:

- Profile height:
 - Range 1: 0–100 μm ($\pm 2\%$)
 - Range 2: 100–500 μm ($\pm 5\%$)
- Grid overlay accuracy on 8" wafer: $\pm 1 \mu\text{m}$ on full wafer
- Front to backside overlay: $\pm 3 \mu\text{m}$
- Absolute form accuracy from lens-like free-form elements
 - Range 1: $\pm 1 \mu\text{m}$ (RMS)
 - Range 2: $\pm 5 \mu\text{m}$ (RMS)

Roll to Plate (R2P)

Currently there are many proven processes for textures well below 100 μm height, shrinkage around 5% and industry-compatible manufacturing yields that are highly design dependent. Within PHABULOU S we want to demonstrate the R2P UV imprinting of free-form micro-optical textures with:

- Material development for shrinkage below 4%
- Large-area imprinting (up to 600 mm wide, length of 1 m feasible)
- Imprint alignment below $\pm 100 \mu\text{m}$
- 2-up and/or 4-up tiled replication for high-volume production.
- Texture Height (Depth H) > 200 μm (the ambition is H > 500 μm)
- Pattern fidelity >90%
- Process Yield >90% (product within spec, no air entrapment, no process defects)

Roll to roll (R2R)

The state-of-the-art UV-roll to roll processes are commonly limited up to 10–20 μm standard micro-optical structure (MLA and micro prism) replication to the one-sided polymer film. PHABULOU S pilot line target for the R2R-UV-imprinting of free-form micro-optical structures with:

- Height / Depth H > 50 μm (the target range is $1 < H < 100/150 \mu\text{m}$)
- Yield >90 % (stemming from defect density <10 %) over 250 mm web width
- Pattern fidelity >90%
- Double-side UV imprint replication
- Replication speed >1 m/min (target: 10 m/min) for throughput increase and cost reduction
- Replication length >500 m to demonstrate process reliability and reproducibility

State-of-the-art Technologies

5 - UV imprint materials

Micro-optical applications impose a plethora of optical and mechanical specifications including high imprint fidelity, high optical transparency, tunable/controllable refractive index and typically low optical dispersion for minimizing chromatic aberration. UV-curable materials suitable for replication of optical micro-structures have moderate refractive indexes in the range of n 1.5.

The versatility of the UV embossing process associated to the possibility to adjust the optical properties **can open new perspectives for optical design.**

The PHABULOuS Pilot-Line will be supplied with a complete palette of low to high refractive index **UV-curable materials to compensate for limitations in the manufacturable curvatures and unlock the potential of FMLAs for various applications.**

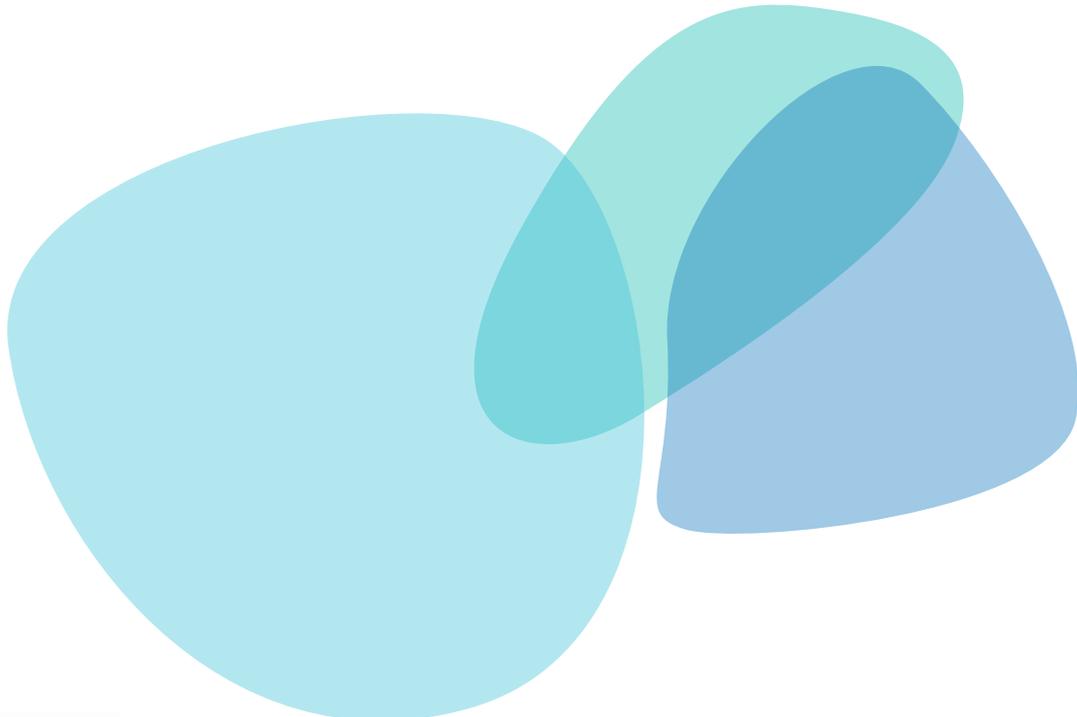
In addition, the specific material composition for arbitrary use cases will be developed to fulfil the appropriate standards (i.e. low cost, high-throughput, large-area replication).

The PHABULOuS ambition is to **formulate novel UV-casting materials** with finely-tuned properties as summarized in the table below.



State-of-the-art Technologies

Optical properties	
Tunable refractive index (1.4 - 1.8 with ± 0.001 precision)	Resin-substrate optical match Strong light bending at moderate surface curvature
Optical quality surfaces (RMS ≤ 10 nm)	Prevent undesired light scattering, thus degradation of the optical function (e.g. stray-light glare)
High UV-light & weather resistance	Long-lived outdoor devices (e.g. PV and daylighting)
Mechanical properties	
Adhesion to substrate (PC, PET, PEN, Glass, Silicon, etc.)	Device robustness and safe de-moulding
Tunable viscosity	Wet layer thickness's from 1 to 100 μm
Shrinkage upon UV-curing (< 5%)	High pattern fidelity (90%)
Tunable elasticity	High scratching resistance and improved flexibility
Tunable surface energy (20 – 70 mN/m)	Defect-free de-moulding



State-of-the-art Technologies

6 - Thin-film coating

Optical coatings on FMLA structured surfaces are desired either for high reflection (e.g. in decorative application) or as anti-reflection (AR) solutions. Maintaining a homogeneous coating thickness is fundamental to achieve the required optical performance but very challenging, specially over large areas.

PHABULOus aims at providing integrated services for optical coatings on FMLA structured surfaces for the three UV imprint replication technologies (wafer, R2P, R2R). With this objective, the PHABULO μ S Pilot Line will offer the following coating technologies.

Pulsed magnetron sputtering – A set of universal adapted pulsed magnetron sputtering process parameters for high-aspect ratio FLMA polymer surfaces will eliminate the need for multiple pre-test iterations for each structure.

Magnetron sputtering - Using both planar and cylindrical targets and a broad variety of plasma modes such as e.g. unipolar (DC, DC pulsed) or bipolar (Sinus, square wave, Pulse-Package modes) as well as a broad variety of target materials including metals (Si, Ti, Ta, Nb, Sn, Ag, Zr, ...) and their oxides and nitrides, as well as transparent conductive oxides (e.g. ITO, AZO, ...).

Magnetron PECVD – Silicon-organic precursor monomers are introduced into the sputtering source to achieve organic-inorganic hybrid coatings for mechanically adapted coatings for flexible applications.

POLAR process – Anti-reflective nano-structures are manufactured on uncoated polymer surfaces using a reactive plasma etching process with a dual magnetron as plasma source. The special features of the structure formation may vary in dependence on both the plasma parameters and the type of polymer. The treatment results in a clear reduction of reflectance as well as the corresponding increase of transmittance.

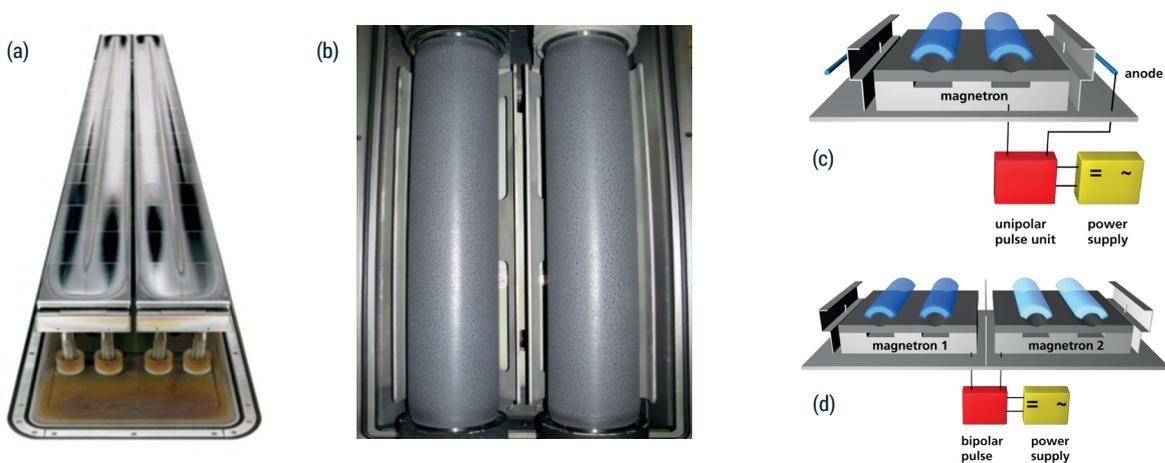


Figure 14: Planar (a) and cylindrical (b) sputtering targets. (c) unipolar and (d) bipolar.

State-of-the-art Technologies

Single-run large area plasma surface treatment at 2 m/min (R2R or moving plates) compatible with <1% residual reflection of the FMLA surfaces.

PHABULOUS holds the capacity for pilot manufacturing on 8-inch wafers, 1000×600 mm² plates and rolls with a width of up to 600 mm and a length up to 500 m.

PHABULOUS holistic service portfolio for optics products combines material and stack design, customer-adapted process development for both highly productive and high precision coatings, pilot-scale material provision as well as key components for industrial scale thin film coating.

It is the ambition of PHABULOUS to offer the mentioned technologies in sheet-to-sheet and roll-to-roll configurations to support all customer and applications.

PHABULOUS offer of optical coatings:

Sheet-to-sheet	
Processes	Reactive magnetron Sputtering Magnetron PECVD Reactive polymer surface etching for Anti-Reflection
Multilayer coatings	Anti-reflective coatings Optical filter designs High-reflection coatings
Materials	Metals: Si, Ti, Ta, Nb, Sn, Ag, Zr, ... Oxides and Nitrides Transparent Conductors: ITO, AZO, etc.
Roll-to-Roll	
Processes	Reactive magnetron Sputtering Reactive polymer surface etching for Anti-Reflection (for many polymers) High Rate PECVD of SiO _x C _y High-rate evaporation of metal layers
Optical Inline Control	Inline-Spectrometer (cross web Homogeneity of Transmission / Reflection) Hyper Spectral Surface Defect Imaging (starting from Oct. 2021)

State-of-the-art Technologies

7 - Quality control

In order to ensure high quality FMLA components, the PHABULOUS Pilot Line will implement **in-line and off-line quality control process** across the complete manufacturing chain i.e. master origination, tool production and UV imprint replication. The quality of the masters, tools and UV imprint replicas will be quantified using novel characterization methods developed by the PHABULOUS Pilot-Line to overcome the limitations of current state-of-the-art quality control.

The PHABULOUS ambition is to optimize the metrology procedure for quick and accurate quality assessment of the manufactured FMLAs. Specifically, we aim to:

- Quickly (>1 cm²/h) measure the microscopic surface profiles of **up to 500 µm** height with lateral, and vertical resolution below 300 and 50nm respectively and surface slopes >60°.
- Perform automatic side-by-side comparisons of designed and measured profiles with **sub-micron** resolution to determine manufacturing limits and quantify progress on tooling and replication
- Translate manufacturing inaccuracies into optical performance degradation by performing ray-tracing simulation from the measured profiles and simulating the true optical performance with an **over 95% accuracy**, thereby offering a genuine quality check, thus de-risking customer decisions.
- Establish non-destructive quality control procedures based on state-of-the-art methodology to detect surface defects on large (≥0.3×1 m²) (free-form) micro-structured optical surfaces and rolls within two days after production.

PHABULOUS characterization methods	
Surface profilometry	Tactile, confocal and white-light interferometry surface profilers Optical Microscopes Atomic force microscopy Field-Emission SEM Surface + Cross-section Imaging
Large Area Surface Inspection	ISRAVISION roll-to-roll surface inspection (300 mm width) Roll-to-Roll monitoring of Transmission and Reflection
Optical Properties	UV-VIS-NIR spectrophotometer with Integration sphere VN-accessory for measurement of absolute reflectance FT-IR-spectrometer in transmittance, reflectance & ATR Haze and gloss measuring Spectroscopic ellipsometry
Material Robustness, reliability, and ageing	Bending and rolling tester with minimum of 1.5 cm bending radius Linear Strain tests (up to 150°C) Outdoor weathering test station Climate chamber for damp-heat-test & temperature-cycle-test Condensation water test and salt spray test Abrasion-Tests: (1) Pencil test; (2) Sand Tickling Test; (3) Taber Abraser
Chemical composition	Element analyses with x-ray fluorescence or EDS or GD-OES

State-of-the-art Technologies

Surface profilometry – The optical response of optical components is strongly determined by their surface profile. In comparison to standard spherical and aspherical optical micro-lenses and micro-lens arrays, MLAs, free-form micro-lens arrays, FMLAs are characterized by more complex geometries such as asymmetrical surface profiles, large aspect ratios, steep angles, etc. that need to be accurately measured.

The PHABULOU S Pilot-Line offers a wide portfolio of State-of-the-art surface analysis characterization tools (see first column in the table above). Their capability to accurately measure complex geometrical features will be quantified and a portfolio / catalogue of relevant solutions and characterization protocols / sequences derived for different types of optical (free-form) micro-structures.

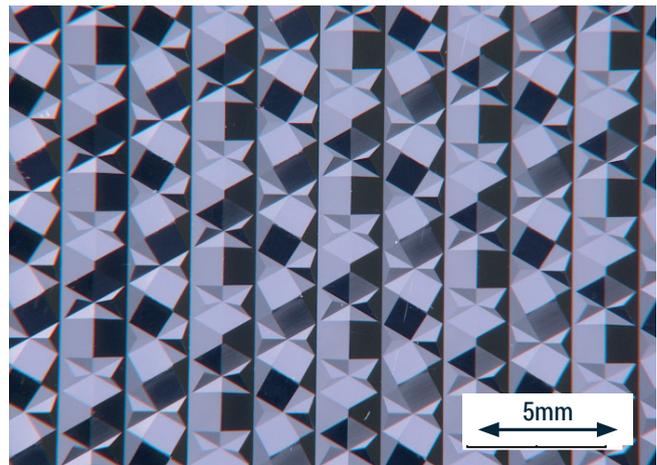


Figure 15: Left) bending/rolling characterization.
 Right) microscope picture of a FMLA

State-of-the-art Technologies

Surface analysis – The presence of thousands to millions (large data sets) of complexly shaped (wide parameter space) individual micro-structures present on each FMLA component makes their quality control a real challenge even when using appropriate surface profilometers.

In order to alleviate this, PHABULOuS uses the recently developed so-called “**semi - empirical characterization method**” (see figure 16), which enables the effective quality control of manufactured FMLA components with complex surface geometries with respect to the customer specifications. This method will be improved for higher efficiency and accuracy. In addition, The PHABULO μ S Pilot-Line will develop effective CAD methods to compare large point clouds (measured surface profiles) and CAD files (nominal designs).

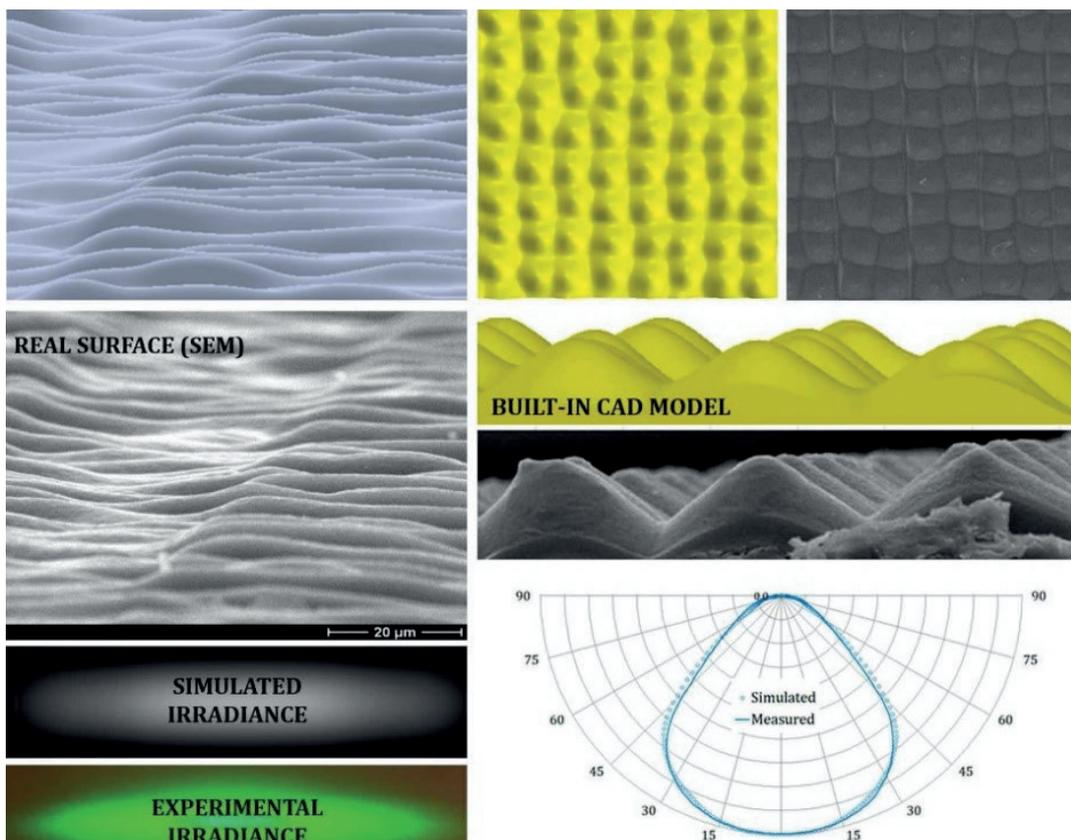


Figure 16: “Semi-empirical characterization method”. CAD models and SEM picture and predicted versus observed performance (left) of a BrightView E1060 asymmetric diffuser. BrightView G-CG90 de-glaring foil (right). Predicted and measured luminous intensity of a de-glared OLED (bottom right).

State-of-the-art Technologies

Surface quality – Surface quality (low roughness) is known to downgrade the performance of all optical components, including FMLAs. Surface roughness can be measured with the available surface profilometers. However, the associated impact on performance cannot be easily predicted. Ray-tracing, the most efficient and widely used predicting approach cannot deal with surface roughness due to the short lengths of the involved features (≤ 100 nm). Efficient routes need to be developed to incorporate surface roughness into the PHABULOUS quality control process.

Other important properties will be measured and reported including material optical properties, stability and large-area uniformity using PHABULOUS wide range of **characterization methods**. Where necessary, existing state-of-the-art methods will be optimised and upgraded **beyond-state-of-the-art** to improve their capability for the evaluation of FMLAs.

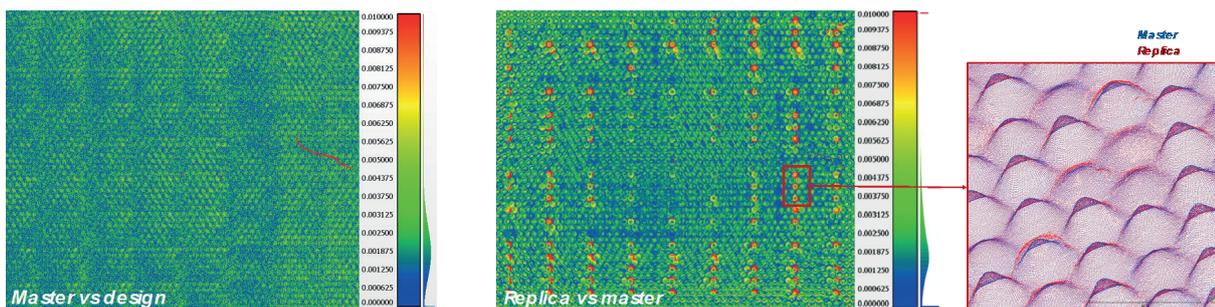


Figure 17: Surface analysis: Left) The surface roughness of the Master is compared to the Design and is virtually identical to it. Right) the Replica is compared to the Master. The replica shows relatively good form accuracy, however localized large deviations observed. Software packages used, SolidWorks, Rhinoceros, ReSurf, CloudCompare and Leica-Cyclone.



State-of-the-art Technologies

8 - Product Integration

PHABULO μ S delivers product integration processes in which photonic and electronic devices/ components can be assembled on substrates. Currently assembly of devices is performed using high accuracy pick-and-place machines providing alignment accuracy of $\pm 7 \mu\text{m}$ (3σ value) operating in both S2S and R2R mode on 200 mm wide sheet/web. Minimum device size is $100 \times 100 \mu\text{m}^2$. Assembly of SMD components can be performed using high speed and accuracy R2R assembly line operating up to 300 mm wide web. Line total length is 18m and it can be operated also in S2S mode. Maximum component pick-and-placement speed using Fuji NXT III Dyna Head system is 27'000 CPH. Minimum component size is 0402 ($1 \times 0.5 \text{ mm}^2$). Optical structure layer can be integrated on top of lighting layer using passive or active alignment methods. Typically, passive alignment methods provide up to 5-10 μm and active alignment methods down to 1 μm accuracy between layers. Integration of functional layers can be performed using lamination, UV-welding and adhesive bonding.

Both S2S and R2R assembly and integration processes will be evaluated and developed towards specific use case applications requirements during the course of project. A new 2-arm 6-axis alignment and adhesive bonding equipment providing 20 nm linear resolution and 0.005° angular resolution will be evaluated and applied in integration processes within PHABULO μ S project.

State-of-the-art Technologies



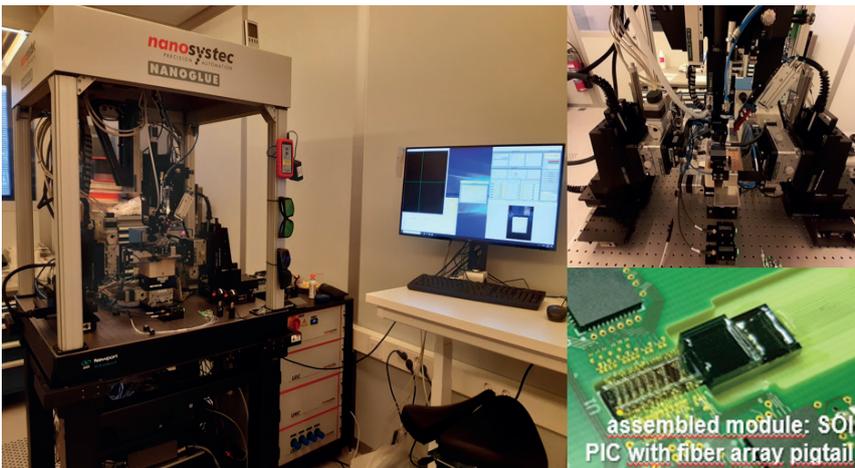
Figure 18: S2S and R2R assembly machine examples

Top) S2S/R2R device assembly machine Datacon 2200EVO.

Centre) High speed S2S/R2R SMD assembly line and Fuji NXT III pick-and-place machine.



Bottom) New 2-arm 6-axis S2S alignment & assembly machine.



assembled module: SOI PIC with fiber array pigtail

Market Applications

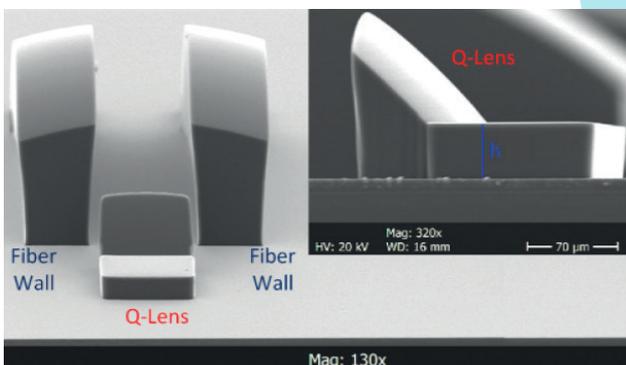
Various market applications for free-form micro-optics



Micro-lens arrays for lighting



Micro-displays for AR / VR / MR

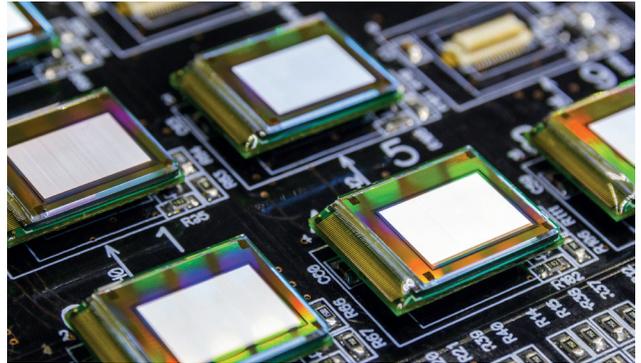


Free-form optics for photonic integrated circuits PICs

Market Applications



Automotive lighting



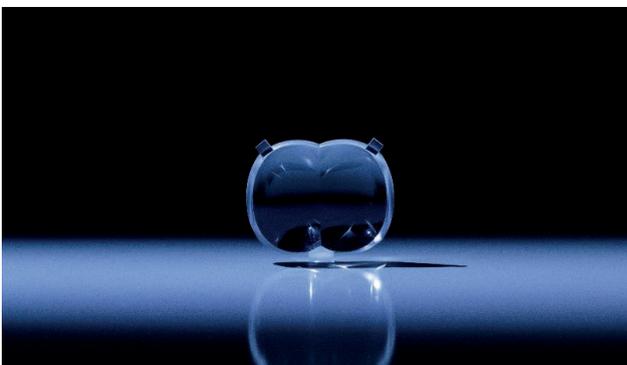
Micro-displays



Solid-state lighting



Luxury



Virtual reality

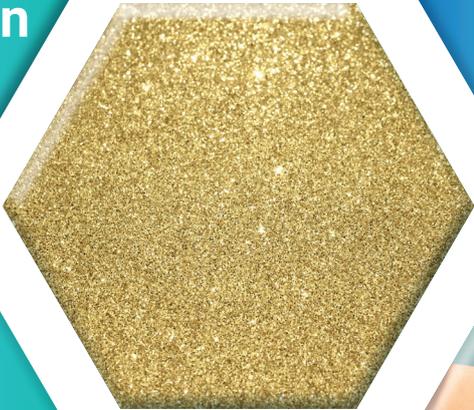


Transportation interior lighting



Optical communication

Health care & Life sciences



Security & Branding



Decoration & Luxury



Consumer electronics



Market Applications

Advanced FMLAs for VR, AR & MR

LIMBAK started in PHABULOUS as an European SME developing and licensing extreme-performance optics in the field of Virtual Reality (VR), some of these branded ThinEyes and comprising radically free-form MLAs.

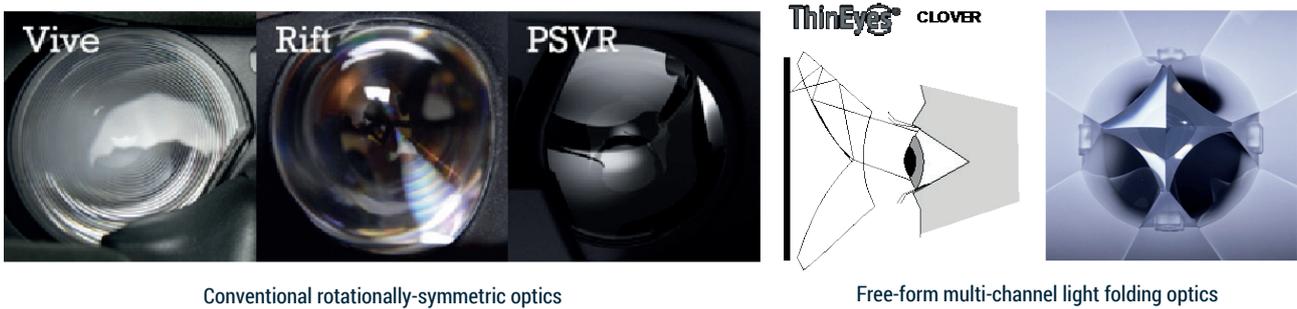


Figure 20: State of the art optics in commercial headsets are based on rotationally symmetric lenses (left). New headsets in 2020 are starting to be advanced optical trains, like the free-form multi-channel light-folding CLOVER lens (right), by LIMBAK

That is the case of TRENZA, one of the most advanced ThinEyes concepts. The technology can lead to video-see-through MR headsets with the size of sunglasses and superior Field of View (FOV) and angular resolution.

TRENZA is a super-thin (8-10 mm only) optical technology based on a set of free-form micro-lens arrays (MLAs) stacked between a display and user eyes designed to produce an image of the former onto the latter with the features needed in an immersive experience. Within the PHABULOUS project, LIMBAK has designed one of these variations, observing the pilot lines manufacturing constraints expected after acceleration of manufacturing services.

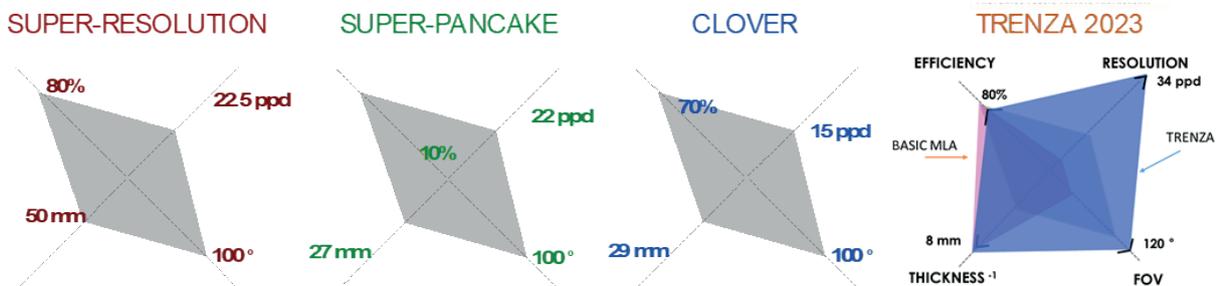


Figure 21: TRENZA 2023 as aimed to developed within PHABULOUS, benchmarked against the state of the art

Market Applications

PHABULOuS has showed its capability in manufacturing complex structures as where needed for the unique features of TRENZA and is looking forward to other customers in the AR/VR domain to come forward with their specific needs and specifications.

Design - The MLAs of this design include 4 arrays of free-form lenses working in parallel, through ~ 300 optical channels. TRENZA requires the advanced optical manufacturing technologies available within PHABULOuS Pilot Line.

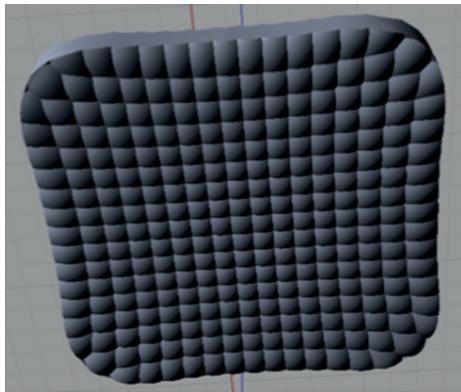
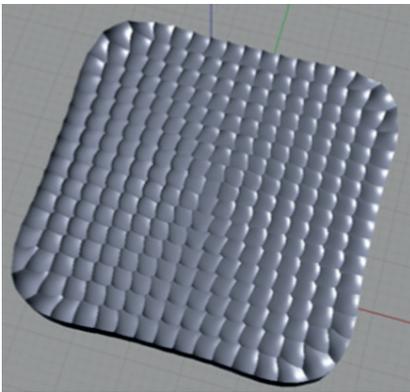
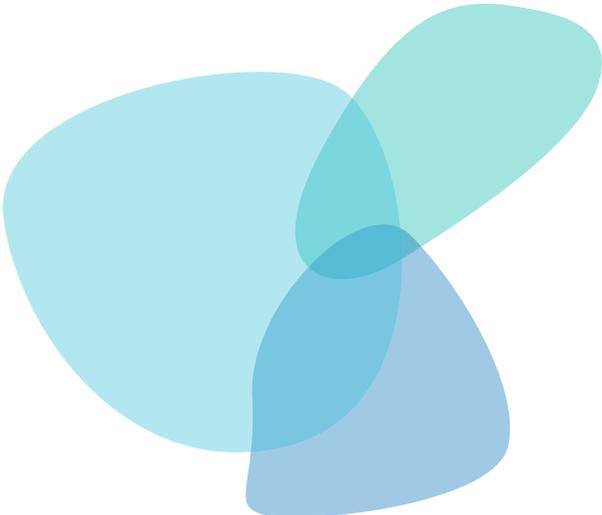


Figure 22:

Top: TRENZA 2-side MLA optical stage designed within PHABULOuS Pilot Line

Bottom: Master created within PHABULOuS Pilot Line



Advanced FMLAs for OLED micro-displays

MICROOLED provides cutting-edge near-eye AMOLED displays and modules for a wide range of products, including high brightness ultra-low-power microdisplays for light AR eyewear products. In addition, under its ActiveLook® brand, the company is providing a groundbreaking light AR eyewear solution that brings a truly heads-up, hands-free experience to industry, sports, medicine and more.



Free-form microlens arrays (FMLAs) provide great advantages for improving pixel luminance of OLED micro-displays, especially for Augmented Reality (AR) applications with see-through glasses.

Design - Main goal for MICROOLED was to control the angular shape of light output and to enhance brightness of the OLED micro-display components, especially in connection with compact, free-space optics based micro-projection systems for wearable Augmented Reality applications.

Origination - The design is characterized by a small pitch in the order of 5µm together with a high aspect ratio. PHABULOuS provided the possibility to study different methods for mastering. Finally, origination is now done both by using silicon etch technologies (CEA-Leti) as well as by laser grayscale lithography (Nanocomp), where the latter provides highest aspect ratio.

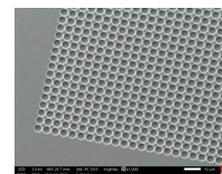


Figure 23:
 FMLA master by Si-etching

Replication - Replication is done on 200mm glass wafer by SUSS MicroOptics using a suitable polymer material. Final assembly to the microdisplay chips is then performed by CEA-Leti.

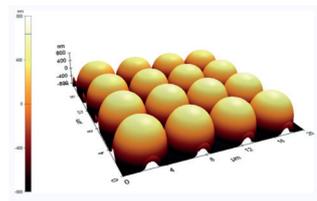


Figure 24: Replicate of FMLA master

MICROOLED will evaluate performance and manufacturability of different designs of micro-optical elements in order to choose the right manufacturing process for industrialisation of the technology.

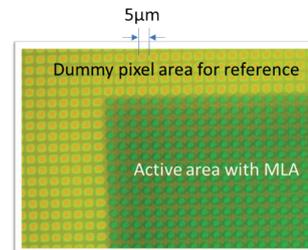


Figure 25: Assembly of FMLA replicate on microdisplay pixel matrix.

"PHABULOuS provides for us an excellent opportunity to realize and test small pitch/ high aspect ratio microlens arrays to enhance performance of our low power light AR solutions and to evaluate different solutions for future industrialization."

Gunther Haas, CTO & co-founder MICROOLED



Advanced FMLAs for large area direct-lit LED luminaires

SEISENBACHER is a global provider of interior solutions for the railway industry. As one of the use case partners in PHABULOUS, they are working on their next generation of luminaires with integrated free-form micro-optics for rail vehicles, buses and other means of transport.

Free-form microlens arrays (FMLAs) have the ability to produce square/rectangular illuminance patterns upon LED illumination. The individual illuminance patterns produced by each LED on an array can hence be overlapped with 100% fill factor thus rendering a uniform luminance over the luminaire outermost surface (exit aperture).

Design - SEISENBACHER joined PHABULOUS looking to develop ultrathin luminaires (thickness <10 mm) or luminaires with a significantly reduced number of LEDs (less than half for linear lighting) and a customized shape of illumination pattern due to free-form micro-optical films. The image shows the design of the free-form structure used per light source, realizing a very homogeneous irradiance on the diffuser plane.



Figure 26: Design used per light source.

Origination - Besides the FMLA design, the pilot-line partner Joanneum Research further supports SEISENBACHER with the manufacturing of the FMLA master (image). The quality of the master is key for the optical appearance and has therefore to be produced with a high accuracy ensuring an outstanding surface quality. The inspection of the existing masters showed a perfect match with the light technical simulations done in the design phase.

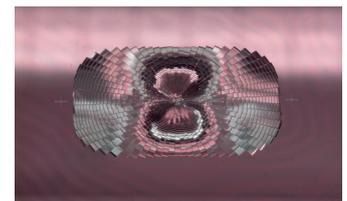


Figure 27: FMLA master

Tooling / Upscaling - In the next process step, the master is upscaled by Joanneum Research into a so-called multi-lens-array. CSEM, a further pilot-line partner, is then responsible for providing the final tool for replication, which is the galvanized multi-lens-array (image). Every single step in the process chain is of course accurately monitored to guarantee a high-quality FMLA output.

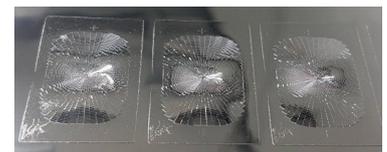


Figure 28: Galvanized multi-lens array



Replication - The replicas of the optical structure are only as good as the master and the tool produced during the upscaling process. The pilot-line partner of SEISENBACHER for the replication, Morphotonics, are producing those replicas using their UV-imprint R2P (roll-to-plate) technology.

The image shows the replica (FMLAs imprinted onto a substrate), which will then be further processed and prepared for the integration into the final product.

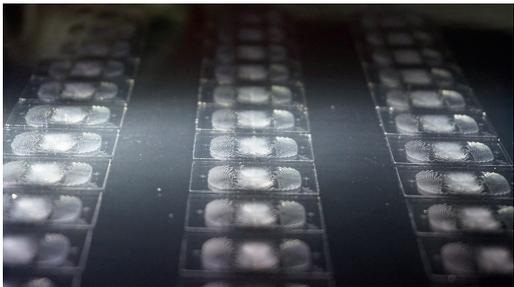


Figure 29: Replica of FMLAs imprinted onto a substrate

Integration - The image shows the final micro-optics in comparison with a ten Euro-Cent coin. The integration into the SEISENBACHER luminaires has been finished and a comprehensive type test campaign is ongoing to prove the compliance of the final product with the harsh environmental conditions on railway rolling stock applications.

The SEISENBACHER goal to miniaturize optical systems for interior lighting applications with the use of free-form micro-optics is on the right track.

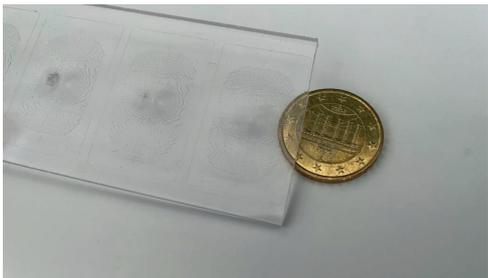


Figure 30: Final micro-optics in comparison to a 10 Euro-cent coin



"The PHABULOuS project is setting the further development of free-form micro-optics on an all-new path. SEISENBACHER is on board as one of the use-case partners, and our idea to develop a new generation of direct-lit LED luminaires with uniform luminance appearance is on a very promising way."

Christian Forstner, Head of R&D at SEISENBACHER

Advanced FMLAs for lighting solutions

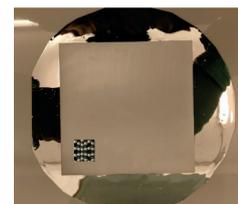
Zumtobel Lighting GmbH is an internationally leading supplier of integral lighting solutions for professional indoor building lighting applications, targeting the fields of premium lighting solutions including, luminaires, emergency, controls and Digital Services for various building lighting application areas. As a use case of PHABULOuS they are looking to develop luminaires with asymmetric uniform light distribution.

Free-form micro-lens arrays (FMLAs) are more cost-effective, thinner and lighter than reflectors and have demonstrated potential to efficiently produce asymmetric light distributions and uniform illuminance patterns. With over 70 years of profound experience in developing optics for general lighting application Zumtobel is able to specify optical elements which meet ergonomic, human and regulatory requirements.

Design - The design was realized by Zumtobel. To achieved a high asymmetric distribution which has to be in addition very homogeneous, as the eye is very sensitive to inhomogeneity, a continuous shape was chosen. This shape incorporated steep angles, which is one of the major challenges for the technology as a whole.



Origination - For the origination different technologies have been benchmarked. The Pilot-Line partners Joanneum Research, PowerPhotonic, Wielandts UPMT and LASEA made sample coupon of the design in different scales. Very good surface quality and shape matching the design could be achieved. For the final step master of the size up 100mm in diameter have been manufactured. Alternative to manufacture a large master also the Step & Repeat (S&R) process of Joanneum Research have been implemented.





Replication - The partner Morphotonics and SUSS MicroOptics made replica on plate. For the high structure heights shrinkage is very likely to happen, but imprints of very good shape precision have been produced. Joanneum Research and Nanocomp made imprints in Roll-2-Roll (R2R) technology for lower structure heights also those were of good quality.

Quality control - After each manufacturing step quality control is important. With several partner of the Pilot Line, Fraunhofer FEP, Wielandts UPMT, SUSS MicroOptics, PowerPhotonic and Morphotonics, measurement could be linked to the simulation results and so the optical performance of the analysed.



"The collaboration with PHABULOUS generated a lot of know-how, using these technologies, to create optics for general lighting applications. The increase of the capabilities of the Pilot-Line is impressive."

Katharina Keller, Director Optics at Zumtobel

Market Applications

Advanced FMLAs for next generation headlights

HELLA GmbH & Co. KGaA, now operating under the overarching umbrella brand FORVIA, is one of the larger automotive suppliers worldwide and one of the use case partners in the PHABULOuS project. PHABULOuS and HELLA are combining strength and knowledge in their field to develop the next generation headlights that incorporate free-form micro-optics.



Free-form micro-lens arrays (FMLAs) are aesthetically appealing and provide high potential for reducing installation space, reducing weight and enable low-cost manufacturing. With HELLA's insights into the requirements of the automotive markets and the specific needs and wishes of HELLA several steps have already been made towards finding a free-form micro-optics- based solution.

Design - The idea of the HELLA design concept is the generation of a double-sided FMLA, using a structure for pre-forming the light on the light entrance side and a free-form facet structure on the light output side. Latter shows a large number of micro-facets that are oriented and arranged in a specific way to generate the light distribution on the street and reduce the stray light to a minimum. The image shows one of the different designs that are used to find the best combination of facet height and orientation and manufacturability of the free-form structure.

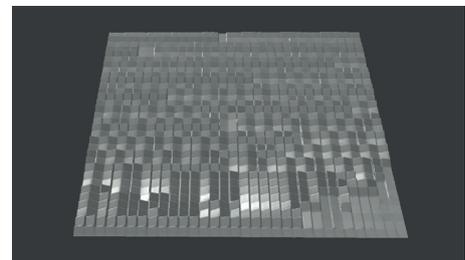


Figure 31: one of the tested structure designs realizing a low beam function.

Origination - The pilot-line partners that support HELLA with the manufacturing process are Wielandts UPMT and PowerPhotonic. As the first optical surface adapts the light shape for the facet structure, the quality of this surface mainly influences the performance of the overall optic. Using their ultra-precision machining technique, Wielandts UPMT generated first masters of this structure, which was in a first step designed as a micro-Fresnel lens, with high accuracy and an impressive surface quality. The core of the FMLA, the facet array, was mastered by PowerPhotonic. After adapting the facet structure to the manufacturing parameters of their laser material processing technology, the resulting masters matched the simulations perfectly.

Market Applications



© HELLA GmbH & Co. KGaA



Replication - The replicas of an optical structure are only as good as the masters. But with regard to the facet design of HELLA, a perfectly customizable and highly precise process is the second cornerstone for a satisfactory result.

Both pilot-line partners of HELLA for the replication, SUSS MicroOptics and Nanocomp, showed within the first replication trials, that they are not only able to replicate the master structures but also to accurately combine the two functional surfaces of the entry and exit side in one component. The result of the first replication test run is a double-sided micro-optic as small as a one cent coin and only between 0.3mm and 2.5mm thick.

With regard to the targets of HELLA, to take advantage of free-form micro-optics to miniaturize optical systems for headlamp applications, the developments supported by the PHABULOuS Pilot Line are on a promising way.

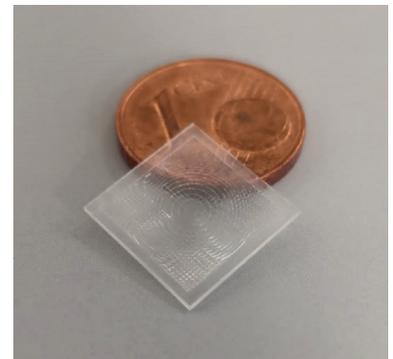


Figure 32: As small as a one cent coin – and even thinner: one of the double-sided FMLA replicas produced by Nanocomp.

"For this project, we have chosen one of the most challenging applications and started with a concept on research-level. But the first results prove the potential of free-form micro-optics and the valuable contribution of the PHABULOuS pilot-line for this promising technology."

Dr. Daniela Karthaus, Optical Engineer at HELLA



Advanced FMLAs for luxury foils

D. Swarovski KG defines its business by the mastery of crystal cutting and passion for innovation and design. As one of the use cases in the PHABULOUS project, Swarovski is looking for ways to bring brilliance to a larger scale using free-form micro-optics to create large sparkling surface foils and panels with high brilliance.

Free-form surface micro-structuring can provide high brilliance for foils and panels, expanding design freedom and opening the door to new designs. The high quality and cost-effective large-area roll-to-roll (R2R) and roll-to-plate (R2P) replication technologies offered by PHABULOUS are very interesting for such applications.

Design - The design for the free-form micro-optics structure in this use case was developed by Swarovski and is based on the faceted-structure of cut crystals. Different regular and irregular one- and double-sided structures were created and evaluated - always aiming for the highest sparkle.

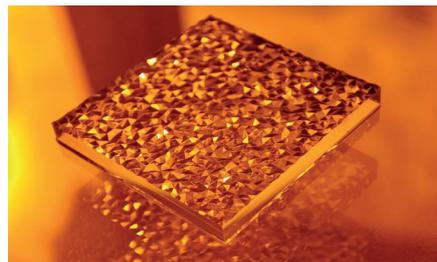


Figure 33: Faceted structure developed by Swarovski.

Origination - Two different technologies were tested for Mastering: Laser ablation and ultra-precision diamond ruling. Partners involved were Joanneum Research, PowerPhotonic and Wielandts UPMT. While laser-based methods require up-scaling by stitching, diamond ruling is directly done on a drum and thereby creates a completely seamless master. Based on tests in the internal Swarovski Light Engineering Lab and visual appearance two structures were selected due to their high-sparkle and diamond-like appearance:

- One-sided irregular structure produced via laser ablation (PowerPhotonic)
- Double-sided irregular structure created via diamond ruling (Wielandts UPMT)

Replication - Roll-2-roll replication was done by Joanneum Research and Nanocomp. Furthermore Master 2 was successfully replicated roll-2-plate on a glass substrate by Morphotonics. Silver mirror on the back of the structure was applied roll-2-roll by Fraunhofer FEP.

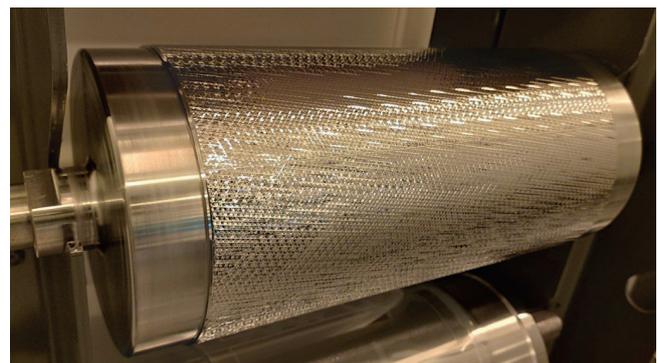
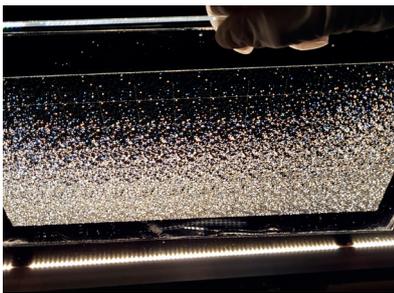


Figure 34: Roll-2-Roll replication of crystalline structure.

SWAROVSKI

Demonstrators – Various kinds of sparkling demonstrators were created within this use-case, e.g.:

- Direct imprint of one-sided structure on glass, no mirror
- Light boxes with one- and double-sided structure on PET carrier foil, no mirror
- PET carrier foil with one- and double-sided structure and mirror on one side
- PET carrier foil with one- and double-sided structure with mirror and additional print



*Figure 35. Use case samples:
 Top left: direct imprint on glass panel
 Top right: unmirrored foil with back light
 Bottom left: mirrored foil
 Bottom right: mirrored foil with additional print*



"Our project partners within PHABULOUS did a great job in imitating the sparkle and structure of real crystals using free-form micro-optics. This technology offers an enormous potential to embellish large surfaces and will amaze customers around the globe."

Philipp Hangartner, Platform Management Components at D. Swarovski KG

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